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Fuel Cell Introduction into a Class 8 Truck

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ABSTRACT

A state-of-the-art Peterbilt 385 tractor was specified and procured for a multiphase program designed to develop a fuel cell powered class 8 tractor. Five fuels were used in baseline engine exhaust emissions testing of the tractor and for baseline performance determinations of the vehicle. The alternative fuels (a B20 biodiesel blend, synthetic Fischer-Tropsch diesel) and a ultra low sulfur CARB equivalent diesel fuel achieved significantly lower emissions test results than the baseline United States Environmental Protection Agency (EPA) certification diesel fuel. A petroleum JP-8 aviation turbine fuel demonstrated higher unburned hydrocarbons than the EPA certification fuel but this is thought to be due primarily to the low viscosity of the JP-8 interfering with fuel injector efficiency. Vehicle acceleration performance with the alternative fuels was so similar to the EPA certification fuel that it is doubtful that drivers would notice the difference. A baseline computer model of the vehicle using Rapid Automotive Performance Tool for Optimization and Reporting (RAPTOR) software was run and validation against the baseline emissions runs seems to be quite good. A Rapid Prototype Electronic Control System (RPECS) to control the tractor, hydrogen system and fuel cells was designed to be capable of handling the next two years' equipment as well as the future full-scale diesel reformer/fuel cell hybrid electric vehicle. A ProEngineer Computer Aided Design (CAD) model of the tractor and hydrogen fuel system was prepared to facilitate placement of new components on the tractor.

Electrification of engine loads including the engine cooling system and air conditioning system were studied. Two each 2.5 Kilowatt (kW) Solid Oxide Fuel Cell APUs were received in October 2002. SwRI began to define vehicle interface requirements based on input from General A hydrogen storage and supply system was physically installed on the Peterbilt tractor and a plan for modeling was initiated. As progress is made with Solid Oxide Fuel Cell (SOFC) technology, the reformer to mate with the SOFC will be markedly different from current reformers and remains the critical path to achieve the final goal of the project, which takes input from and feeds information to the Army's 21st Century Truck Program. [1]*

INTRODUCTION

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A state-of-the-art Peterbilt 385 tractor was specified and procured for a multlphase program designed to develop a fuel cell powered class 8 tractor. Five fuels were used in baseline engine exhaust emi88iona testing of the tractor and for baseline performance determinations of the vehicle. The alternative fuels (a 820 biodleael blend, synthetic FischerTropsch diesel) and a ultra low sulfur CARS equivalent diesel fuel achieved significantly lower emissions test results than the baseline United States Environmental Protection Agency (EPA) certification diesel fuel. A petroleum JP-8 aviation turbine fuel demonstrated higher unburned hydrocarbons than the EPA certification fuel but this is thought to be due primarily to the low viscosity of the JP-8 interfering with fuel injector efficiency. Vehicle acceleration performance with the alternative fuels was so similar to the EPA certification fuel that It is doubtful that drivers would notice the difference. A baseline computer model of the vehicle using Rapid Automotive Performance Tool for Optimization and Reporting (RAPTOR) software was run and validation against the baseline emissions runs seems to be quite good. A Rapid Prototype Electronic Control System (RPECS) to control the tractor, hydrogen system and fuel cells was designed to be capable of handHng the next two years' equipment as well as the future full-scale diesel reformer/fuel cell hybrid electric vehicle. A ProEngineer Computer Aided Design {CAD) model of the tractor and hydrogen fuel system was prepared to facilitate placement of new components on the tractor. Electrification of engine loads including the engine cooling system and air conditioning system were studied. Two each 2.5 Kilowatt (kW) Solid Oxide Fuel Cell APUs were received in October 2002. SwRI began to define vehicle interface requirements based on input from General A hydrogen storage and supply system was physically installed on the Petelbilt tractor and a plan for modeling was initiated. As prograas is made with Solid Oxide Fuel Cell (SOFC) technology, the reformer to mate with the SOFC will be markedly different from current reformers and remains the critical path to achieve the final goal of the project, which takes input from and feeds information to the Army'a 21 81 Century Truck Program.

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The U.S. Army is interested in electrification of diesel engine loads in order to improve the efficiency and exhaust emissions of it's systems, achieve enhanced silent watch capability, ease cooling loads to tightly packed radiators and decrease the space claim of a bare engine by moving loads to off-engine locations. It may be possible to increase the life of components by only running them when needed or at lower speeds.

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*Numbers in brackets refer to references.

Fuel cells offer clean, quiet, and potentially very durable systems. For the Army, one of the key technologies necessary for utilizing fuel cells is a diesel reformer/fuel cell system. Earlier work, evaluatingdiesel reformer technology, indicated that diesel reformers are still 3-5 years away from being able to reliably produce enough reformate to power a fuel cell for class 8 tractor propulsion. [2] This program takes a stepped approach
to achieving this goal and achieves electrification of diesel engine loads as well.

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A project to introduce fuel cells into a class 8 tractor in a phased approach, with the ultimate goal of demonstrating a diesel fuel reformer/fuel cell/hybrid electric drive train was initiated in 2001 to closely mirror the U.S. Army's vehicle requirements and provide parallels to commercial trucking applications. While fuel cells and fuel cell ancillary systems are evolving rapidly, there are no liquid fuel reformer/fuel cell systems currently available to fully power the propulsion needs of a class 8 tractor.

This project takes a multi-year approach to this challenge by first procuring a state-of-the art class 8 tractor and utilizing a (3 to 20 kW) hydrogen-fueled fuel cell as an auxiliary power unit (APU) on the tractor. Year two of the program assesses diesel engine parasitic loads (including water pump, cooling fan and others) and begins to electrify these loads, with the goal of increasing overall system efficiency. Year two also has the goal of procuring a larger fuel cell, possibly a reformer/fuel cell. Year three of the program converts more diesel engine parasitic loads to electric drive. If the technology is available, year four of the program will integrate a full diesel reformer/fuel cell hybrid electric tractor design.

Computer models to assess the baseline truck systems and examine the impact of each phase of the changes are utilized and a strong technology assessment task runs throughout the program in order to keep pace with technological developments and assure that the program utilizes state-of-the art systems.

This report summarizes project progress and program status to date and provides background to future reports.

DISSCUSSION OF RESULTS

Baseline Performance Determinations

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Baseline performance determinations were to encompass testing of the Class 8 tractor under repeatable conditions. After the vehicle was broken in, the first test was to be a coastdown test to determine vehicle constants, such as aerodynamic and rolling resistance factors. Acceleration tests were to be performed at truck empty weight plus a cargo weight, to obtain acceleration data, hill climb, and startability on grade.

This section documents the baseline performance testing for the SunLine Transit Peterbilt 385 tractor. These tests include coastdowns to determine drag coefficients and acceleration runs with five different fuels. The fuels used in these determinations, listed in Table 1 Test Fuels, were EPA Certification D2 Diesel, California ultra-low sulfur diesel fuel (ULSDF), JP-8 (military jet fuel), synthetic F-T gas-to-liquid (FT GTL) diesel fuel and Biodiesel (B20 blend in ULSDF). SwRI performed testing January 2002.

Peterbilt Motors Company manufactured the SunLine tractor, VIN number 1XP-GD58X-2D581457, in December 2001. The truck had a GVWR of 46,160 pounds, and was powered with a 2001 model year Cummins ISL 8.9L, I-6, turbo-charged, diesel engine rated at 330 bhp at 2,100 rpm. It was equipped with a 10-speed manual transmission and super single tires. SwRI broke in the truck by driving it on the highway with a load. The odometer showed that the truck had accumulated 3,348 miles with 65.1 engine hours before performance testing.

Coastdown Test Procedures

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The objective of this work was to generate baseline aerodynamic and rolling drag coefficient data from a Peterbilt tandem-axle tractor and trailer. The Peterbilt 385 tractor pulled a flatbed trailer with concrete blocks for ballast for a total truck/trailer weight of 53,220. The truck was taken to a stretch of road two hours south of San Antonio and run between

the towns of Los Angles, TX and Fowlerton, TX. This area was chosen for its low traffic and level, smooth roads. Following SAE procedure J2263 the tractor and trailer were taken through a series of runs in alternating directions with four runs in one direction and four runs in the opposite direction until a total of forty runs were completed. Time, speed, and weather conditions were all recorded and averaged to arrive at a drag coefficient Cadmium (Cd) of 1.01 for the truck and trailer. From this Cd the road load can be calculated, providing more accurate parameters for the computer model.

Acceleration Test Procedures

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The objective of this work was to compare the baseline performance of the Peterbilt 385 tractor and loaded trailer running Certification EPA No. 2 diesel to the five other fuels listed in Table 1. These five fuels were stored in separate ten-gallon fuel tanks that were placed behind the cab. The test fuels tank directly replaced the OEM fuel tank on the tractor and allowed SwRI to maintain the OEM fuel delivery system on the truck. In order to prevent cross-contamination between the fuels, a test fuel tank was purchased for each fuel, and the fuel system was flushed out with the new test fuel after each test fuel was run.

For this series of tests, SAE procedure J-1491 was followed. This entailed taking the tractor-trailer through a series of six runs in opposing directions, accelerating from 30 to 60 mph. Since the tractor has a ten speed manual transmission, and driver shifting inconsistency could adversely affect the test, the truck was accelerated in a single gear for these tests. Ninth gear was selected to run this test because of its capability to operate over the speed range, eliminating driver error associated with shifting the transmission. Figure 1 Acceleration Runs, summarizes the acceleration runs with the test fuels with six runs averaged together for each fuel. The graph shows that there are only small differences in performance between the five test fuels. This indicates that environmentally friendly fuels, such as the Fischer Tropsch gas to liquid fuel can be used without penalizing performance.

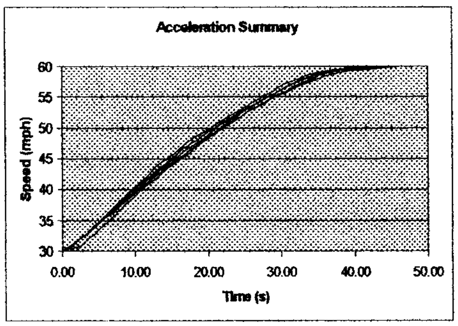

Figure 1 Acceleration Runs

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Table 1 Test Fuels		
Fuel Name	**VRD Fuel Code**	**Fuel Code**
Cert. EPA No. 2 Diesel	VE-0271	CL01-1005
JP-8 Aviation Diesel	VE-0269	CL01-1004
20% Biodiesel Blend	VE-0274	CL01-989
ARCO ECD-1 Diesel	VE-0270	CL01-985
Fischer-Tropsch GTL Synthetic Diesel	VE-0273	CL01-1025

In addition to the 30 to 60 mph tests, a set 0 to 60 mph tests were run under the same testing regime using the diesel fuel in the OEM fuel tank. These runs were not used in the fuel comparison since the shifting uncertainty creates a situation where the data is more of a test of the driver, and not the individual fuel. The results of these tests show an average 0 to 60 mph acceleration time of 65.2 seconds. After the truck and transmission are more broken in, a better 0 to 60 time might be possible due to better shift times. At the time of testing, with a relatively new transmission, shift time between gears was up to 2 seconds.

EMISSION TEST PROCEDURES

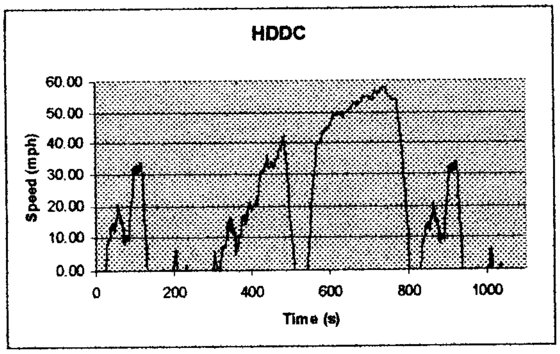
The objective of this work was to generate baseline fuel economy and exhaust emissions data from a Sunline Transit-Peterbilt tandem-axle tractor truck. Exhaust emissions test data was generated using the step-by-step test plan given in Table 2.

TABLE 2. SUNLINE TRANSIT BASELINE EMISSIONS TEST PLAN

Step	Description
1	Perform emission measurement system and chassis dynamometer system checks and calibrations.
2	Set system inertia to 48,300 pounds. Install the truck on the heavy-duty chassis dynamometer.
3	Isolate on-board fuel system, and provide fuel from a drum containing the first specified fuel in Table 1.
4	Perform coast downs to establish as-installed system rolling resistance load as a function of vehicle speed. Establish dynamometer load to achieve required simulated road load. Set up to acquire information necessary to process emission test-related data.
5	Perform practice-driving cycles to check dilution tunnel settings and instrument ranges.
6	Perform the following test sequence, measuring emissions of HC, CO, CO_2, NO_X, and PM. a. Set road load at 50 mph b. Run prep "Heavy-Duty Urban Dynamometer Driving Schedule" to warm engine to stabilized conditions c. 15-minute engine-off soak d. Run first hot-start test for specified fuel e. 15-minute engine-off soak f. Run second hot-start test for specified fuel g. 15-minute engine-off soak h. Run third hot-start test for specified fuel i. Disconnect fuel and connect to remaining fuels specified in Table 1 j. Run truck at idle until 4 gallons of fuel is purged into waste container k. Operate vehicle to 50 mph to verify load setting l. Repeat steps b-k for remaining fuels
7	Remove truck from chassis dynamometer.
8	Summarize and report results.

The test cycle to be used in this program is the EPA specified Urban Dynamometer Driving Schedule for Heavy Duty Vehicles. The test cycle, shown in Figure 2 Heavy-Duty Dynamometer Driving, covers a distance of 5.5 miles over 1,060 seconds. Tests will be run in accordance with the procedure outlined in Table 2 and will be performed repetitively three times for one of the five Diesel fuels, yet to be determined; D2 Diesel which meets EPA certification specifications, JP-8, Arco ECD-1, a 20 percent Biodiesel blended with ECD-1 (B20), and a Fischer-Tropschs fuel. For each set of tests, the engine will be fueled from a 55-gallon drum of the appropriate test fuel. Hot return fuel from the engine will be routed through a heat exchanger to prevent the fuel in the drum from heating. In addition, a purge routine will be used during initial fuel change, to rid the system of the previous fuel. Fuel analysis specifications are given in Attachment A.

Figure 2. Heavy-Duty Dynamometer Driving Schedule



The fuel consumption during the test will be measured to provide an accurate comparison between the baseline and the modified tractor. The test procedure for obtaining fuel mileage is done during the emissions testing. The data from the emissions testing will be processed and fuel economy will be calculated using the carbon balance method.

During the cycle, shown in Figure 2, gaseous and particulate emission measurements will be made using procedures outlined in an 1979 EPA report titled "Recommended Practice for Determining Exhaust Emissions from heavy-duty Vehicles Under Transient Conditions." Emissions of total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO2), and oxides of nitrogen (NOX) will be measured during transient testing. Following diesel engine testing protocols, total hydrocarbon and NOX concentrations will be continuously monitored in the dilute exhaust over each test and the integrated results used in computing emissions. NOX correction factors for engine intake air humidity will be applied as specified in the transient FTP for diesel fueled engines. Nondispersive infrared (NDIR) instruments will determine the concentrations of CO and CO2 in the proportional dilute exhaust bag samples. Concentrations of HC, CO, CO2, and NOX will be processed along with CVS flow parameters and vehicle operating parameters to compute mass emissions on the basis of distance (g/mi.). These computations are based on equations specified in the CFR. Particulate emissions will be measured using dilute sampling techniques as specified in the transient FTP for diesel fueled engines. The PM filter media used will be a 90 mm Pallflex T60A20. The CVS flow rate will nominally be 2,000 scfm and single dilution PM sampling techniques will be used to maximize filter mass loading.

The total dynamometer simulated inertia (test weight) of the truck will be 48,300 pounds. Inertia simulation on the SwRI heavy-duty chassis dynamometer uses mechanical flywheels coupled to the driven rolls. Using the EPA Recommended Procedure, the total theoretical road load at 50 mph will be 103.6 hp, based on a calculated rolling resistance of 60.38 hp and aerodynamic influences of 43.23 hp.

Table 3 summarizes the exhaust emission and fuel economy results from the baseline tests performed at SwRI. Exhaust emission results are presented in units of grams per mile.

TABLE 3. SUNLINE TRANSIT BASELINE EMISSIONS TEST SUMMARY

Test	HC	CO	NOx	PM	CO_2	MPG
Fuel	g/mi	g/mi	g/mi	g/mi	g/mi	
EPA CERT	1.06	3.1	14.3	0.68	1,835	5.5
JP8	1.35	3.0	12.8	0.56	1,761	5.4
ECD-1	1.07	3.0	13.1	0.60	1,742	5.6
B20	1.03	2.8	13.4	0.56	1,797	5.4
FT-GTL	0.61	2.7	12.2	0.51	1,703	5.3

% Deviation from Diesel Fuel Meeting EPA Cert. Specifications*

Test	HC	CO	NOx	PM	CO_2
Fuel	%	%	%	%	%

JP8	27.5	-4.8	-10.5	-18.1	-4.0
ECD-1	0.4	-3.5	-8.2	-11.6	-5.1
B20	-2.6	-10.7	-6.3	-17.0	-2.1
FT-GTL	-42.4	-11.6	-14.3	-24.6	-7.2

** - % signifies decrease in emissions from cert. Fuel*

FUEL PROPERTIES AND TEST PROCECDURES

The fuels used to provide baseline performance and exhaust emission data were EPA Certification D2 Diesel, California ultra-low sulfur diesel fuel (ULSDF), JP-8 (military jet fuel), synthetic F-T gas-to-liquid (FT GTL) diesel fuel and Biodiesel (B20 blend in ULSDF). Fuel property data are summarized in ATTACHMENT A. The test methods and data for the fuels are provided in Table A-1. The test methods and data for the biodiesel B100 fuel used to make the biodiesel B20 blend (with ARCO ECD-1) is provided in Table A-2.

The EPA Diesel #2 Certification fuel is used to certify engine exhaust emission level compliance with legal limits at the time of manufacture of the engine. This fuel (coded CL01-1005) has a 50 cetane number, 0.8500 Kg/m^3 density, 345 ppm sulfur, and 34.1 wt% aromatic.

The California ULSDF is manufactured as an ARCO ECD-1 environmentally clean diesel fuel that is CARB (California Air Resources Board) low sulfur fuel equivalent. It would be compliant if the aromatic content were below 10 percent. This fuel (coded CL01-985) has a 57 cetane number, 0.8207 Kg/m^3 density, 7 ppm sulfur, and 19 wt% aromatic. The lower cetane number value of 51.7 by SwRI Ignition Quality Tester (IQT) is believed to be the more accurate value for this fuel and agrees well with the manufacturer's value and the cetane index values.

AGE REFINING, Inc., in San Antonio, TX manufactures the JP-8 aviation turbine fuel to MIL-DTL-83133 specification requirements. This fuel (coded CL01-1004) has a 47 cetane number, 0.7947 Kg/m^3 density, 55 ppm sulfur, and 20 wt% aromatic. The lower cetane number value of 44.9 by SwRI Ignition Quality Tester (IQT) is believed to be the more accurate value for this fuel and agrees well with the cetane index values. The viscosity of this fuel is below the engine manufacturer's minimum recommended guidance value.

The synthetic Fischer-Tropsch GTL diesel fuel was manufactured at the Shell Bintulu refinery. This No. 2 diesel fuel (CL01-1025) has a >75 cetane number, 0.7839 Kg/m^3 density, 0.6 ppm sulfur, and 0 wt% aromatic. A lubricity additive was added to this fuel to improve the lubricity to reduce wear of fuel wetted, load-carrying components of the engine/fuel system.

The Biodiesel B20 blend was prepared at SwRI by adding 20 V% biodiesel (CL01-1003, made from used cooking oil) to the ARCO ECD-1 diesel fuel (CL01-985). This biodiesel B20 blend has a 53.5 cetane number, 0.8330 Kg/m^3 density, 12-PPM sulfur, and 19.3 wt% aromatics. The aromatic data suggests that the biodiesel portion of B20 does not participate in the hydrocarbon analysis when ASTM D 2425 procedure is employed. The cetane number value of 53.5 by SwRI Ignition Quality Tester (IQT) agrees well with the D 613 cetane number and the cetane index values. General guidance for use of biodiesel B20 blends in California is for the biodiesel not to degrade important properties related to diesel fuel quality and exhaust emissions. Since biodiesel made from used frying oils tend to have higher cetane numbers than those for soy bean oil derived biodiesel, B20 biodiesel blends with CARB diesel are expected to be more acceptable for use in California.

Cooling System Electrification.

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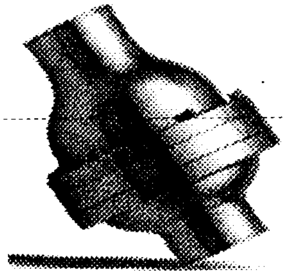
The truck cooling system consists of the cooling fan, radiator, water pump, and thermostat. The review and analysis of the cooling system for potential electrification focused primarily on the electrification of the cooling pump and the engine thermostat. This activity consisted of performing an energy consumption analysis comparison between the existing mechanical water pump duty cycle and the possible duty cycle by implementing intelligent control of an electric cooling pump.

The control available with an electric cooing pump that is not directly coupled with engine speed, but rather is part of an adaptable cooling system based on actual temperature conditions is limitless. Exterior temperature conditions, vehicle speed, and cooling fluid temperature are all parameters that can be taken into consideration for optimum engine cooling. This is not possible with a mechanically coupled cooling pump. Another component not previously available for control is the coolant loop control valve. This control valve replaces the function of the engine thermostat. A proportional three-way control valve, coupled with the electric cooling pump may optimize the cooling system to the changing engine conditions.

Figure 3 High Efficiency Electric Cooling Pump



To initiate our cooling system analysis detailed engine cooling parameters were obtained from Cummins for the ISL engine. Minimum flow requirements, pressure drop across engine, and other factors were gathered from the engine manufacturer. This data was incorporated into, and helped guide, our cooling system analysis.

An electric cooling pump manufactured by Engineered Machine Products (EMP) was identified for substitution onto the Cummins engine. The replacement pump is a high-efficiency cooling pump that has been implemented and proven in similar automotive applications. Performance data for this pump was acquired from EMP for pump duty cycle comparison. The electric pump is depicted in Figure 3 High Efficiency Electric Cooling Pump.

To begin the comparison between the mechanical and electrical based coolant pumps, two energy consumption analyses were performed. The first was an analysis of the warm-up cycle and the second was an analysis of a highway cycle. The warm-up cycle that requires bringing the engine up to operating temperature saw a greater that 25% improvement in energy savings. Figure 4, Cooling Pump Power Consumption for Warm-Up, depicts the power savings between the electric pump and the legacy mechanical unit during engine warm up.

A second duty cycle reviewed for energy savings was vehicle acceleration up to highway speed. Under this condition the higher efficiency of the electric cooling pump would provide most of the energy savings. Figure 5, Cooling Pump Energy Consumption for Highway Acceleration, depicts the greater than 20% energy savings for the highway acceleration duty cycle.

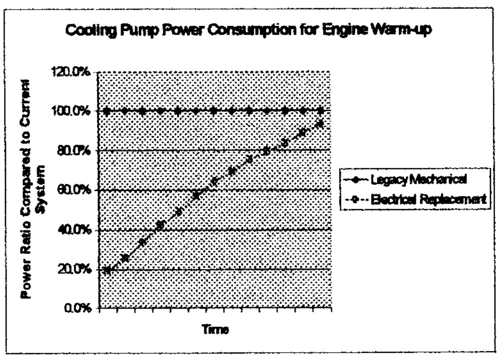


Figure 4 Cooling Pump Power Consumption for Warm-Up

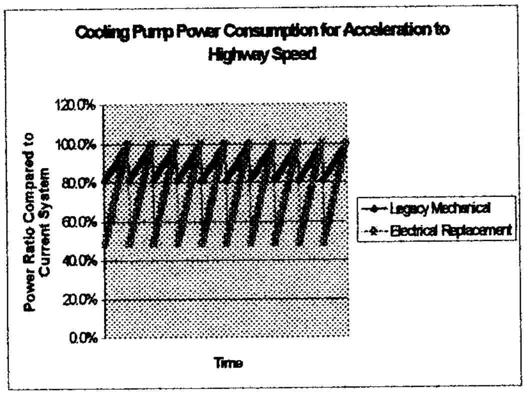


Figure 5 Cooling Pump Energy Consumption for Highway Acceleration

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Air Conditioning System Electrification.

The engine driven air conditioning system on the 2002 Peterbilt 385 is used for maintaining a comfortable in-cab temperature and as a windshield defroster. The Original Equipment Manufacturer (OEM) system includes a Sanden SD7 engine driven compressor that draws approximately 6 kW at full load. One disadvantage of this compressor is that it is the same one that is used on all of their trucks, and therefore it is sized for the trucks with the full size sleeper. Peterbilt and Modine engineers have designed this system to provide up to 25000 BTU/hr of cooling, but advised that 9000 BTU/hr for the day cab trucks is adequate. Other disadvantages of having the engine driven compressor include constant parasitic losses from clutch drag, inability to operate the compressor in its efficient zones, and packaging.

While looking into replacing the OEM mechanically driven compressor with one that is electrically driven, several manufacturers were contacted including Sanden, Masterflux and Delphi, which make variable speed electric compressors. The Sanden and Masterflux compressors are depicted in Figure 6 Sanden and Masterflux Electric Compressors. These electric variable speed compressors are offered in small units rated at approximately 9000 BTU/hr. Electric compressors can achieve overall higher efficiencies than mechanically driven ones because of their ability to run at their most efficient points. Electrically driven compressors do not require an electric clutch that draws power while the air conditioner is on and provide engine drag while it is off. Electric compressors allow great flexibility in packaging, making it possible to mount it anywhere on the vehicle. This is important in many military applications.

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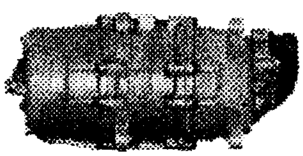

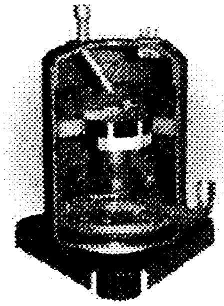

Figure 6 Sanden and Masterflux Electric Compressors

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Other systems explored for vehicle cabin cooling were zeolite beds, and thermoelectrically cooled seats. Zeolite beds can capture waste heat energy from the exhaust and in turn aid the existing air conditioning system through a series of chemical reactions. Thermoelectrically cooled seats use thermoelectric devices that will absorb heat energy, resulting in a cooler seat while using less than 100 watts.

Fuel Cell (APU)

Potential fuel cell suppliers were contacted to determine characteristics of existing fuel cells and manufacturers' willingness to supply a fuel cell(s) for the program. A variety of polymer electrolyte membrane (PEM) fuel cells were anticipated to be available within the timeframe of the program and possibly other varieties as well. Emphasis was to be on availability, robustness in the truck environment, interface requirements, operating characteristics, packaging and cost, not necessarily in that order. As information became available, an evaluation matrix was created and made available to program participants so that they could choose the fuel cell that maximized program benefits. For this first fuel cell, compressed hydrogen was selected as the fuel, since it would simplify vehicle systems somewhat and is available at pressure at SSG. A cost sharing and support agreement from manufacturers was sought.

Based on information on the fuel cell and vehicle specifications, vehicle interface requirements for the fuel cell system were determined. This included bus voltage, cooling requirements, mounting considerations, maintenance accessibility, safety considerations, controls interfaces, clearance requirements, exhaust requirements, operational limits, data accessibility (instrumentation), and other parameters that affect installation and operation with the vehicle.. Emphasis was on a system that is transparent to the operator and easy to service, while maximizing utilization of the fuel cell and allows for upgrading to the next fuel cell. This effort could involve travel to the fuel cell manufacturer to better understand interface requirements. A 42-volt Direct Current (DC) bus voltage was chosen to align with future automotive bus voltage initiatives. The work of defining vehicle interface requirements is ongoing, as General Dynamics was chosen as the fuel cell APU supplier.

The 42-volt fuel cell, made by Acumentrics and packaged by General Dynamics was delivered in October 2002. The system consists of two each 2.5 kilowatt hydrogen fed solid oxide fuel cells for a total output of 5 kilowatts. The power out of the fuel cell is used to charge a 7kilowatt-hour battery from which the electrical loads are drawn. This battery is sized large enough to handle the 1.5 hour startup and shutdown time of the fuel cell and handle other small 42-volt electrical loads until the fuel cell starts to produce power. For the larger electrical loads during fuel cell startup, such as the water pump and the air conditioner, there is an engine driven alternator that will supply 42 and 14 volts dc. This brushless alternator, made by Niehoff, will supply the full 5 kilowatt load until the fuel cell comes on-line, and will then disengage on the 42-volt side at that point, but will continue to supply the 12-volt bus.

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Hydrogen Storage/Supply System

Based upon the requirements of the fuel cell, vehicle, and fuel dispensing systems, an initial systems design of the hydrogen storage system for the truck was performed. The system was to consist of compressed hydrogen tank(s), tank mounting system, heated primary fuel pressure regulator, secondary fuel pressure regulator, over-pressure/over-temperature relief system, filter, interconnection piping, driver instrumentation, coolant piping/valves, manual and automatic valves, excess flow valve(s), signage and other hardware necessary for the implementation of the hydrogen storage/supply system. The system was sized to supply the initial fuel cell as well as the larger year two fuel cell system. Emphasis for the hydrogen storage/supply system was be on safety, ease of operation and durability. The initial design was to consist of flow diagrams and equipment specifications.

In cooperation with multiple tank manufacturers the Specification for a hydrogen storage system was developed and a system by Dynetek was chosen. The three composite Dynetek BTCV-074-C8 tanks have a liquid volume of 216 L, and are capable of internal pressures of 5000 psig. This hydrogen storage system is capable of holding five kilograms of hydrogen, which equates to running the five-kilowatt fuel cell at full power for eight hours before refueling.

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Baseline Modeling

Baseline computer modeling of the existing tractor-trailer to better understand energy flow within the system was performed. The basic parameters of the vehicle such as weight, frontal area, engine horsepower, basic duty cycle, etc., were considered in an attempt to better understand where energy goes within the current system. This baseline model was to be refined and validated with additional data from performance determinations and other data gathered later in the project. The baseline modeling is expected to evolve into a full vehicle "testbed" to perform "what if" scenarios on the vehicle. As part of the baseline modeling effort information was sought on aerodynamic losses, tire rolling resistance, vehicle component drag, component efficiencies and other parameters that affect the model.

Preliminary SunLine vehicle simulations were completed during December 2001. A vehicle data file was constructed, and where actual SunLine vehicle data was sparse, data from similar vehicle systems was appropriately scaled for use in the simulation. A 3242 second EPA urban and highway combined drive cycle was assembled and a preliminary simulation run was completed with a run time of 9.2 seconds. The simulated vehicle had an EPA urban fuel economy of 2.2 mpg and an EPA highway fuel economy of 3.6 mpg, resulting in an EPA combined fuel economy of 2.6 mpg.

Following the preliminary vehicle simulation, the models and vehicle data files were iteratively refined. The trailer model was refined to incorporate a brake model and weight transfer of the trailer and its effects on the tractor.

In parallel with the simulation effort, model validation has begun. The validation includes fuel economy validation against dynamometer data and performance metrics validation against actual vehicle road measurements.

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SUMMARY AND RECOMMENDATIONS

Numerous technology providers were contacted and catalogued during the performance of the project. Truck manufacturers in the United States were communicated with for the purpose of learning which energy efficient features were available on different truck models and which manufacturers were interested in working with this program. Coordination was established with NAC and SwRI personnel working in the Army's 21st Century Truck program to assure the groups were moving in a parallel direction to the 21st Century Truck program.

A state-of-the-art Peterbilt 385 tractor was specified and procured for the project. The lightweight tractor incorporates energy efficient features that will benefit the project throughout the life of the vehicle. SwRI took receipt of the tractor, completed baseline engine exhaust emissions testing of the tractor using five test fuels and completed baseline performance determinations on the vehicle. The alternative fuels achieved significantly lower emissions test results than the baseline United States Environmental Protection Agency (EPA) certification diesel fuel. JP-8 demonstrated higher unburned hydrocarbons than the EPA certification fuel but this is thought to be due primarily to the low viscosity of the JP-8 interfering with fuel injector efficiency. Vehicle acceleration performance with the alternative fuels was so similar to the EPA certification fuel that it is doubtful that drivers would notice the difference.

A baseline computer model of the vehicle using Rapid Automotive Performance Tool for Optimization and Reporting (RAPTOR) software was assembled and run. Validation against the baseline emissions runs seems to be quite good.

A Rapid Prototype Electronic Control System (RPECS) to control the tractor, hydrogen system and fuel cells was specified and proposed. The system is designed to be capable of handling the next two years' equipment as well as the full-scale diesel reformer/fuel cell hybrid electric vehicle.

A ProEngineer Computer Aided Design (CAD) model of the tractor and hydrogen fuel system was prepared. This model will facilitate placement of new components on the tractor.

Electrification of engine loads including the engine cooling system and air conditioning system were studied. Limited modeling of the cooling system indicates that an electrically driven system will save energy, although the overall effect on the vehicle fuel economy may be negligible. SwRI initiated contacts with Engineered Machine Products (EMP) to move forward with the electrification of the cooling system and identified two candidates for electrically driven air conditioning compressors.

Two each 2.5 Kilowatt (kW) Solid Oxide Fuel Cell APUs from General Dynamics/Acumentrics have been specified and procured. These units are expected in August 2002. SwRI began to define vehicle interface requirements based on input from General Dynamics Communication Systems (GD). SwRI began a Software Design Plan (SDP) for the modeling of the fuel cell.

A hydrogen storage and supply system was specified and procured from Dynetek/Enviromech. The unit was physically installed on the Peterbilt tractor and a SDP for the modeling of the hydrogen system was initiated.

The Zeopower Corporation was contracted to examine the feasibility of using waste heat from solid oxide fuel cells to drive a zeolite based air conditioning system. This work is still in progress.

As progress is made with Solid Oxide Fuel Cell (SOFC) technology, the reformer to mate with the SOFC will be markedly different from current reformers. The diesel reformer remains the critical path to achieve the final goal of the project. Numerous companies are working on diesel reforming with some claiming to have accomplished it for short run times. As steps to the final goal of a diesel reformer/fuel cell hybrid electrically driven tractor, it is recommend to following the phased approach of installing and evaluating of the GD/Acumentrics SOFCs, installation and evaluation of a larger or liquid fueled fuel cell the following year, followed by the specification, procurement, integration and testing of a full-scale diesel reformer/fuel cell hybrid-electric drive-train. Maintaining a strong technology evaluation phase to the project to assure that it is partnered with the proper groups in the reformer/fuel cell arena is recommended.

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Appendix A: Test Fuel Properties

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TABLE A-1. DIESEL FUEL PROPERTY DATA REPORTED TO SwRI DEPARTMENT OF EMISSIONS RESEARCH

Property	Units	ASTM Method	JP-8 CL01-1004	ARCO ECD-1 CL01-985	Biodiesel Blend B20 CL01-989	Shell Bintulu Fischer-Tropsch GTL CI01-1025	EPA Diesel #2 Certification. Fuel CL01-1005
Density at 15°C	Kg/m^3	D 4052	0.7947	0.8207	0.8330	0.7839	0.8500
API Gravity	@60°F		46.5	40.8	33.3	40.9	34.9
Distillation		D 86					
IBP	°C		145.5	180.1	182.5	208.0	190.5
10%	°C		161.8	203.9	206.4	246.1	222.2
20%	°C		167.9	213.2	221.2	263.8	238.2
30%	°C		175.1	224.4	235.7	276.9	249.4
40%	°C		182.1	235.4	251.3	289.7	258.0
50%	°C		189.8	247.1	268.7	300.1	266.2
60%	°C		199.0	259.8	287.1	308.7	274.2
70%	°C		209.8	274.5	305.4	315.9	283.7
80%	°C		221.7	291.5	320.9	323.1	296.0
90%	°C		235.6	313.6	333.2	332.0	313.0
95%	°C		244.2	330.3	340.5	338.6	328.1
End Point	°C		253.1	343.4	348.7	344.2	342.9
Residue	Percent		1.1	1.4	0.7	1.4	1.6
Ignition Quality Tester (IQT) Cetane Number		SwRI	44.9	51.7	53.5	NR	NR
Cetane Number		D 613	47	57.3	53.5	>74.8	49.8
Cetane Index		D 976	42.1	52.6	53.3	78.1	47.1
Cetane Index		D 4737	44.8	53.6	53.2	93.5	46.9
Kinematic Viscosity at 40°C	cSt, or mm^2/sec	D 445	1.15	2.18	2.51	2.39	2.65
Flash Point	°C	D 93	42	48	57	88	75
Elemental							
Hydrogen	Wt%	D 5291	14.02	14.28	13.84	14.66	12.72
Carbon	Wt%	D 5291	87.37	85.96	83.67	83.92	86.3
Oxygen	Wt%	Diff.	14.02	14.28	2.49	1.42	0.98
Nitrogen	Mg/g	D 4629	2.8	0.00	9.4	<1.0	74.9
Sulfur	Wt%	D 2622	0.0066	<0.001	0.0012	<0.001	NR
Sulfur	ppm	D 5453	54.9	7.0	12.0	0.6	345
Sulfur	Wt%	D 4294	NR	NR	NR	NR	NR
Hydrocarbon Type:							
Total Aromatics	Wt %	D 5186	20.2	19.1	19.3	0.7	34.1
Mono	Wt %	D 5186	17.4	17.5	17.6	0.5	23.6
Poly (Di+Tri)	Wt %	D 5186	2.8	1.6	1.8	0.3	10.6
Paraffins	Wt %	D 2425	49.6	51.1	51.1	94.7	40.8
Naphthenes	Wt %	D 2425	34.7	33.0	33.0	5.2	29.9
Total Water	ppm (mass)	D 6304	122	125	186	114	152
Color		D 1500	<0.5	0.5	1.5	<0.5	1.5
Appearance, Clear & Bright		D 4176	Clear & Bright	Clear & Bright	Clear & Bright	Clear & Bright	Fail-cloud Form at Apex
Particulates	mg/L	D 6217	0.0	0.66	0.17	0.0	1.2
Copper Strip Corrosion, 3 hr at 50°C		D 130	1A	1B	1A	1A	1A
Cloud Point	°C	D 2500	-50	-12	-9	+3	-17
Pour Point	°C	D 97	-51	-21	-15	0	-24
Freeze Point	°C	D 2386	-49	-8	-6	+2	-12
Carbon Residue (on D 86 10% bottom residue)	%	D 524	0.08	0.08	0.05	0.00	0.11
Acid Number	mg KOH/g	D 664	<0.01	<0.01	0.18	<0.01	<0.01
Net Heat of Combustion	MJ/kg	D 240	43.03	43.01	41.91	44.28	42.81

TABLE A-1. DIESEL FUEL PROPERTY DATA REPORTED TO SwRI DEPARTMENT OF EMISSIONS RESEARCH

Property	Units	ASTM Method	JP-8 CL01-1004	ARCO ECD-1 CL01-985	Biodiesel Blend B20 CL01-989	Shell Bintulu Fischer-Tropsch GTL CI01-1025	EPA Diesel #2 Certification. Fuel CL01-1005
Gross Heat of Combustion	MJ/kg	D 241	46.00	46.05	44.85	47.39	45.51
Lubricity							
HFRR (60°C)	μm	D 6079	NR	NR	NR	NR(450 *)	513
BOCLE Scuff Load	Kg	D 6078	NR	NR	NR	NR (3.8 *)	3.4
Smoke Point	mm	D 1322	23.8	NR	NR	NR	NR
Naphthalenes	V%	D 1840	1.82	NR	NR	NR	NR
Copper Strip Corrosion, 2 hr at 100°C		D 130	NR	NR	NR	NR	NR
Kinematic Viscosity at –20°C	mm^2/sec	D 445	3.52	NR	NR	NR	NR
Steam Jet Gum	mg/100mL	D 381	10	NR	NR	NR	NR
Electrical Conductivity	PS/m	D 2624	0	NR	NR	NR	NR
Icing Inhibitor, DIEGME	%v	D 5006	0.10	NR	NR	NR	NR

NR signifies no results

* Signifies the Shell Bintulu Fischer-Tropsch GTL (CL01-1025) with additive Infinium R690. The new fuel code is CL02-052.

TABLE A-2. BIODIESEL B100 DATA

Property	Units	ASTM Method	Biodiesel CL01-1003 (Manufacturer's Certificate. Of Analysis)
Particulates	mg/L	D 6217	NR
Workmanship	C&B	D 4176	Clear & Bright
Flash Point	°C	D 93	(>120)
Water and Sediment	% Vol	D 2709	(0.02)
Total Water	ppm	D 4928	NR
Kinematic Viscosity @ 40°C	mm^2/s	D 445	4.50
Sulfated Ash	% mass	D 874	(<0.01)
Sulfur	ppm	D 5453	3.8
Copper Strip Corrosion		D 130	(1A)
Cetane Number		D 613	54.8 (51.0)
Cloud Point	°C	D 2500	3 (4)
MCRT	% mass	D 4530	
Neat			0.000269
10% Bottoms			0.269
Acid Number	mg KOH/g	D 664	0.80 (0.27)
Free Glycerin	% mass	D 6584	0.004 (0.012)
Total Glycerin	% mass	D 6584	0.750 (0.118)
Phosphorus Content	% mass	D 4951	NR
Distillation Temp, Atmospheric Equivalent Temperature 90% Recovered	°C	D 1160	NR